A Dual-Port, Dual-Polarized and Wideband Slot Rectenna For Ambient RF Energy Harvesting

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***Abstract*—A dual-polarized rectangular slot rectenna is proposed for ambient RF energy harvesting. It is designed in a compact size of 55 × 55 ×1.0 mm^3 and operates in a wideband operation between 1.7 to 2.7 GHz. The antenna has a two-port structure, which is fed using perpendicular CPW and microstrip line, respectively. To maintain both the adaptive impedance tuning and the adaptive power flow capability, the rectenna utilizes a novel rectifier topology in which two shunt diodes are used between the DC block capacitor and the series diode. The simulation results show that RF-DC conversion efficiency is greater 40% within the frequency band of interested at -3.0 dBm received power.**

References

Index Terms— ***Dual-port rectenna, Slot antenna, Broadband rectenna, rectifier, Impedance tuning***

I. Introduction

Recently, internet of things (IoT) represents one of emerging wireless technologies. It promises the connection of devices (machines, sensors, and other objects) to the internet so that they can become part of recent wireless communications networks [1, 2]. Self-powered electronic devices have gained significant attention in a wide range of applications including wireless sensor networks, smart buildings and the IoT. In many instances, the devices will be portable and wireless and need batteries, which will have finite life and therefore need to be replaced periodically. As IoT expands and the need for much longer operation of the IoT devices increases, the number of batteries that need to be replaced will become prohibitive and unsustainable.

In order to manage the aforementioned issue, harvesting ambient radio-frequency (RF) energy using rectifying antennas (rectenna) represents a promising approach [3]. Rectennas have been proposed for use in wireless power transmission (WPT) for many years [4]. Nowadays, the wireless environment is rich of electromagnetic radio waves (EM) in the frequency range of 0.7-4.0 GHz (2G, 2G , 4G, 5G, and WiFi). Therefore, the power density of ambient RF signals has become sufficient to make ambient RF energy harvesting feasible for the support of self-powered devices in IoT. However, the very low RF power density represents a major challenge in harvesting ambient RF energy. To overcome this, several antenna solutions have been proposed: (1) multiband and broadband antennas are very promising as they are able to receive RF signals from multiple frequency bands like designs in [4-7]. In [4], a novel Hexa-band rectenna that covers a part of the digital TV, most cellular mobile bands and WLAN bands. Broadband antennas. In [7], a broadband dual-polarization cross dipole rectenna has been designed for RF energy harvesting over frequency range on 1.8-2.5 GHz. (2) antennas for wireless energy harvesting (WEH) should have the ability of receiving wireless signals from different polarization. Therefore, rectennas have polarization diversity like circular polarization [7]; dual polarization [8] and all polarization [9] are very promising as they have excellent performance in-terms of RF-to-DC power conversion efficiency. (3) The use of rectenna array [10] or multi-port rectenna [5, 6, 9] increases the level of the harvested RF ambient energy. Increasing the number of array element can enhance the level of harvested energy but this at the expense of large size of rectennas design. Therefore, it has been proved that increasing the number of antenna ports in the same area as the frequency increases, increases harvested ambient RF energy [5]. One more advantage of using multi-port antenna element is the compactness of the overall design. Therefore, the need for a compact, multiband or broadband, and multi-port rectennas represents the current trend in WEH field.

In-terms of the shape of the antenna structure, commonly used antennas for rectennas are like microstrip antenna [6], frequency independent antennas like Bow-Tie antennas [11], dipole antennas, monopoles [2], and 3D antenna structures, which make rectennas difficult to design and for mass production [5]. Unlike the aforementioned antennas structures, relatively little attention has been paid on the design of the slot antenna for dual polarization WEH applications. Therefore, this paper proposes a dual-port; dual polarized printed slot rectenna for broadband WEH applications in the frequency range of 1.7 to 2.7 GHz. Several isolation techniques have been proposed [3-12]. Decoupling networks represents one isolation techniques between MIMO antennas [3, 4]. In [5, 6], parasitic decoupling element technique have been proposed between coupled antenna elements. Although this technique is very effective in achieving excellent antenna isolation over a wide operational bandwidth, it is not suitable for frequencies below 1 GHz as the parasitic decoupling element represents a distributed circuit that resonates based on its dimensions, which are quite large for such frequencies,. Good isolation level has been achieved using defected ground plane structures [7-9]. However, such modifications on the ground are not acceptable for mobile phone devices as the operation of other devices and circuits depends on the ground as well. Other techniques such as the neutralization line [10,12], and the periodic structures [13] are also investigated and proposed as decoupling techniques. However, all of the aforementioned techniques share common drawbacks such as: a difficulty of realization for frequency applications below 1 GHz, especially, when the space is limited. Also, at lower frequencies (below 1GHz) the ground plane acts as a part of the antenna radiator; this makes the isolation between MIMO antenna elements over the same system ground plane quite difficult due to strong current distribution on the ground plane. In Section II, the proposed antenna configuration and its characterization are presented. Section III presents the rectifier circuit design and performance parameters of the resulted rectenna. Finally, Section IV concludes the paper.

II. PROPOSED ANTENNA CONFIGURATION

The geometry and the detailed dimensions of the proposed slot antenna are all shown in Fig. 1. The proposed antenna is printed on a 1-mm-thick, double sided copper, FR4 substrate with permittivity 4.3 and loss tangent 0.025. The design utilizes dual-feed, 50 Ohms lines (a CPW feed line and a microstrip feed line) to excite two orthogonal radiation modes. Both feed line are very promising in Rectenna design as they permit the integration of other circuits like, matching circuits, low pass filters and rectifying diodes. The CPW line is linked to Port 1 through a rectangular shorted monopole, the monopole is shorted in order to achieve a wideband feature of Port 2. Both the slot antenna, the CPW and the shorted monopole are etched on the bottom side of the FR4 substrate. Port 2 and the microstrip feed line are etched on the other side of the substrate, it uses capacitive coupling in exciting the proposed antenna. The dimensions of the proposed antenna have been optimized in CST Microwave Studio [12] to achieve broadband operation covering the ambient RF power in the frequency range between 1.7-2.7 GHz.

Both Fig. 2(a) and Fig. 2(b) show the simulated scattering parameters of the proposed antenna. Both ports have a 10-dB return loss bandwidth from 1.7 to 2.8 GHz. The entire 10-dB covered frequency band has an isolation level better than -11 dB. Over most of the covered frequency band, the isolation level is very high, which is better than 50 dB due to the polarization diversity. This similar impedance characteristic of the two ports gives percentage bandwidth of 48.88% (1.7 to 2.8 GHz) for the proposed dual-polarized slot antenna. The realized gain is another important parameter to evaluate the characteristic of antenna structure to be used in ambient RF energy harvesting. The simulation results show that the antenna's gains are almost the same ranging between (2.1-3.0 dBi). The maximum gain deference between the two ports is about 0.33 dBi. Fig. 3 shows the simulated total radiation efficiency, it shows that both ports has total efficiency between 77% and 90 %.

To overcome this, both antenna elements are installed on the same long edge. By doing this, two orthogonal surface current modes are excited on the shared ground plane. Fig. 2 shows the surface current distribution at 850 MHz when one element is excited and the other is terminated with a matched 50 Ω load. Due to the excited orthogonal current modes, the mutual coupling between antenna elements is reduced below -10 dB at 850 MHz. Additionally, as each antenna elements occupies a very small portion of the top and bottom edges of the PCB, this plays an important role in achieving better isolation level than those in the literature [15, 17]. Regarding the higher frequency bands (PCS 1900 and LTE 2500), the isolation is achieved through spatial diversity as the separation distance at these frequencies is quite high (more than half wavelength).

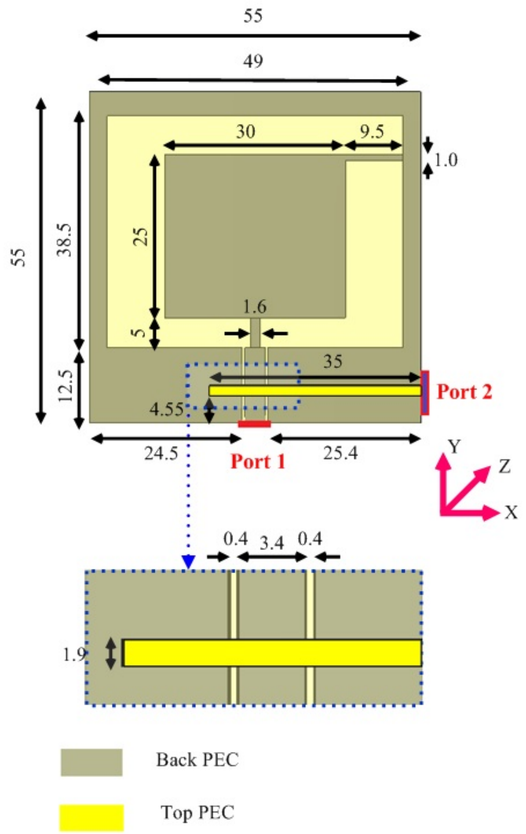
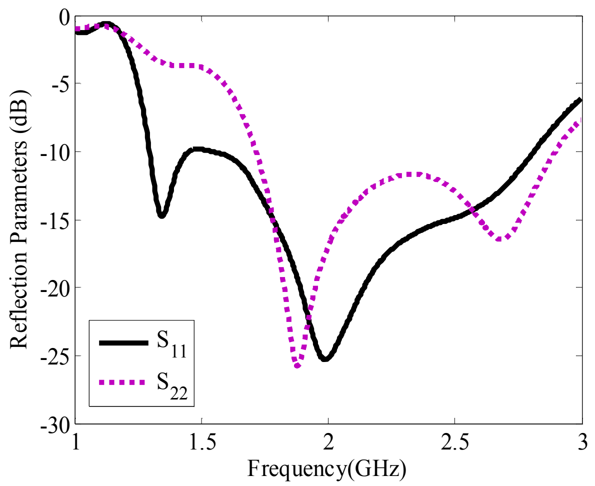
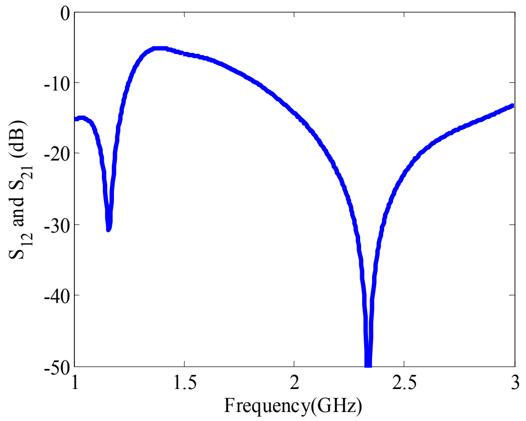


Fig. 1 Geometry of the proposed slot antenna [units are in mm].



(a)



(b)

Fig. 2. Simulated S-parameters of the dual-port slot antenna: (a) Reflection parameters and (b) mutual coupling parameters

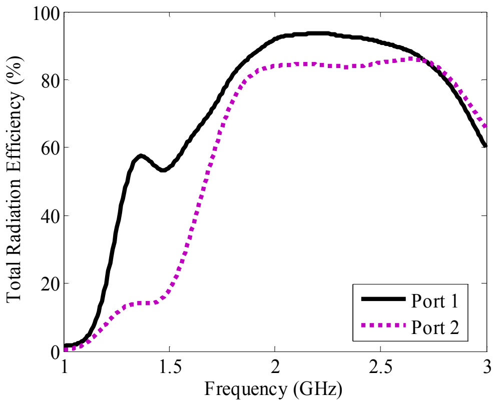
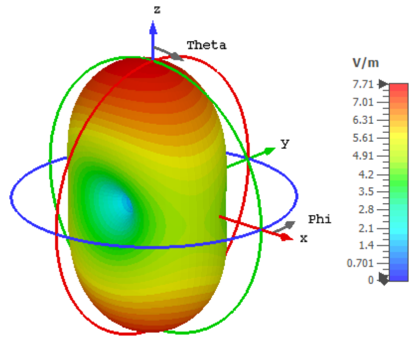
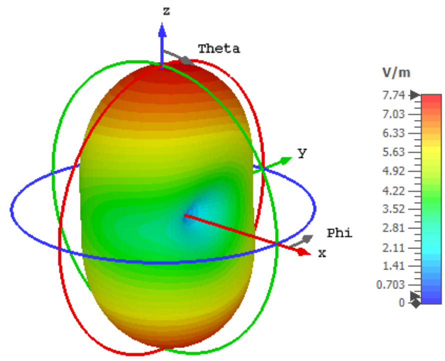


Fig. 3. Simulated total radiation efficiency



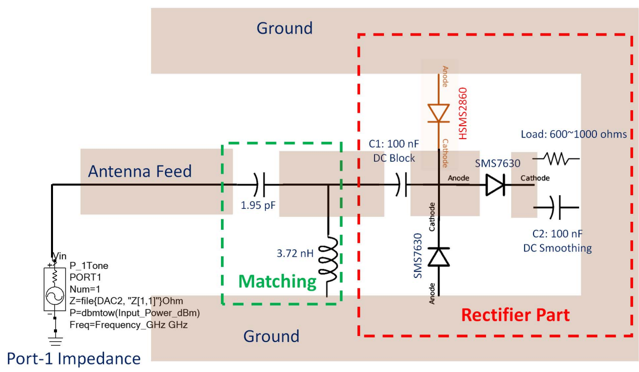
(a)



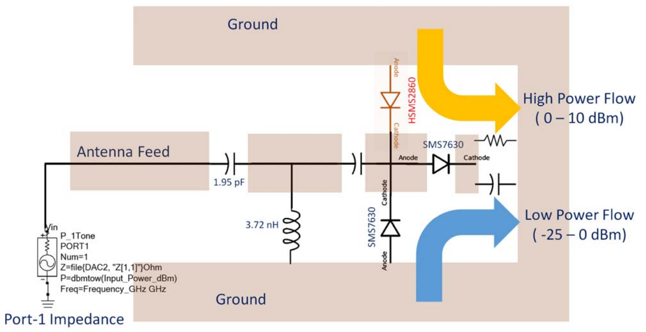
(b)

Fig. 4. Simulated 3D radiation patterns: (a) Port 1 and (b) Port 2

The simulated 3-D radiation pattern of the proposed antenna at 2.0 GHz is attached in Fig. 4. It shows that the radiation patterns of the two ports are bidirectional with a broad beam-width, thus the antenna can receive incident signals from many different angles. Additionally, both far-field components are of different polarization; this means that the antenna is able to receive RF waves with either vertical polarization or horizontal polarization and has demonstrated that the antenna is indeed dual polarization. Overall, the proposed antenna structure represents a good candidate for harvesting RF power.



(a)



(b)

Fig. 5. Proposed adaptive wideband rectifier topology for port 1. (a) Rectifier layout with CPW antenna feed. (b) Adaptive power flow method of the proposed rectifier. The rectifier impedance is tuned by adding the extra shunt diode to match the real part of the antenna impedance over a wide band. The LC matching is used to cancel the imaginary part.

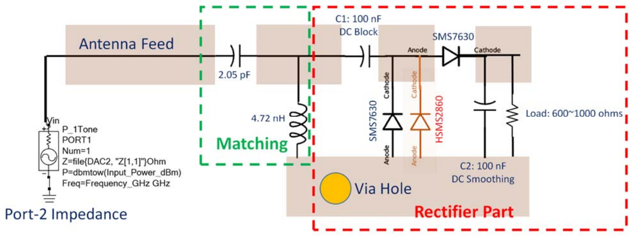


Fig. 6. Proposed adaptive wideband rectifier topology for port 2. The design concept is same as the rectifier for port 1.

III. IMPEDANCE-TUNED ADAPTIVE RECTIFIER CIRCUITRY DESIGN

To integrate the rectifier to the two-port antenna effectively, a co-design method is used here [13]. The antenna impedance (Z-parameter) of ports 1 and 2 are respectively imported to the ADS software as the source impedance of the simulated rectifier circuitry. Hence the rectifier design will be directly linked to the actual antenna impedance as a function of frequency rather than the fixed 50 ohms. Here we propose a novel rectifier topology with a well-tuned impedance and an adaptive power flow capability. The rectifier configuration for port 1 of the proposed antenna is given in Fig. 5 (a). This rectifier is a modified version of a standard voltage doubler circuit under a CPW feeding layout. It is noted that an extra shunt diode is introduced between the DC block capacitor and the series diode (see Fig. 5). The original diodes for the voltage doubler are SMS7630 with a very low forward bias voltage of 0.34 V. However, the additional shunt diode is not necessarily of the same type. In this example, we select HSMS2860 with a forward bias voltage of 0.65 V and a breakdown voltage of 7 V.

The main function of the extra diode is to tune the circuit impedance since most rectifiers could exhibit a strong nonlinearity and high input impedance over a wide band. Having added the extra shunt diode, the impedance of the two shunt diodes (Zshunt) can be written as

$$Z_{shunt} = \frac{Z_{D1}+Z_{D2}}{Z_{D1}Z_{D2}} \quad (1)$$

where Z_{D1} and Z_{D2} are the impedance of SMS7630 and HSMS2860 respectively. With the aid of the extra shunt diode, the real part of the circuit impedance is reduced from around 150 Ω to about 70 Ω over the frequency band of interest (1.7 – 2.7 GHz). Such impedance reductions are reliably observed under -25 to 10 dBm input power and 600 – 1000 Ω load resistance. Therefore, the real part of the circuit impedance will be closely matched to that of the antenna impedance over the wideband. A simple LC matching circuit is used to conjugate match the imaginary part of the rectifier, which is around – 100 and -15 Ω over the desired bandwidth. The optimized LC component values are depicted in Fig. 5 as well.

Also, the cooperation of two different diodes may allow adaptive power flow in the circuit. For example, when the input power is small (-25 to 0 dBm), the threshold voltage of high-power diode branch could not be satisfied, thus the power will flow through the path of low-power diodes. In contrast, if the input power is too high, then the high-power diodes could prevent the circuit from reaching the saturated breakdown voltage level, thus extends the power handling capability and input power range (see Fig. 5 (b)). Such adaptive rectifier configurations will be simpler than previous work who used active switches and bias circuits [14].

The rectifier layout configuration for the second port of the antenna is shown in Fig. 6. The rectifier is designed using the same methodology as used for port 1, but the configuration is switched from the CPW to a microstrip line feed. The LC components are also tuned to match the imaginary part of the antenna impedance at port 2.

The simulated RF-DC conversion efficiency of the two rectifiers versus frequency is given in Fig. 7. The efficiency is evaluated by dividing the output DC power from the harvested RF power from the antenna. In the simulation, both powers can be calculated by using a power meter at the input and output nodes of the circuit. From Fig. 7, it can be seen that good matching performance and high efficiency is achieved at port 1, where the efficiency is higher than 40% over 1.6 – 2.7 GHz at -3 dBm (500 uW). Such a result is reasonable for SMS7630 diodes and comparable with that of the state-of-the-art work in [4–7]. But the performance of port 2 is slightly degraded. The efficiency is over 40% for 1.75 – 2 GHz and 2.4 – 2.7 GHz respectively, and around 35 – 40% within 2 – 2.4 GHz. It can still convert broadband power at an acceptable efficiency. The RF-DC conversion efficiency over a -20 to 10 dBm input power range is shown in Fig. 8. It can be seen that the performance of port 1 and port 2 of the complete rectenna are quite similar at 1.8 GHz. The breakdown point is located at 8 dBm which is larger than that of the typical level of SMS7630 diodes (< 0 dBm [7]). It is shown that the operating power range of the proposed rectenna has been successfully broadened through the introduction of two shunt diodes at different power levels.

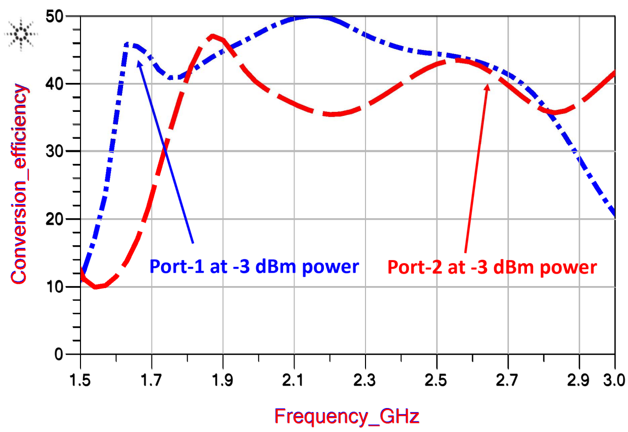


Fig. 7. RF-DC conversion efficiency of two ports vs. frequency.

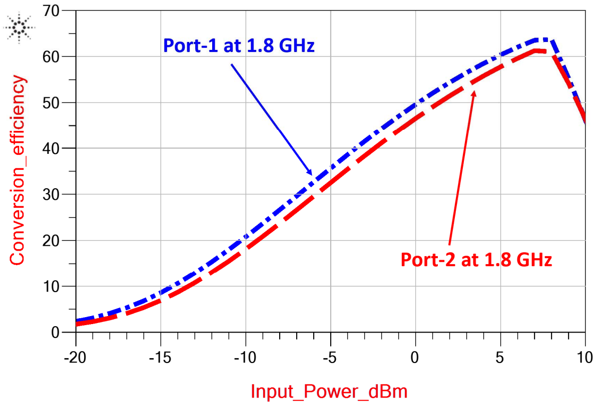


Fig. 8. RF-DC conversion efficiency of two ports vs. input power level.

The next step is to fabricate the complete rectenna with the full integration of the two-port antenna and rectifiers. It is expected that the proposed rectenna could efficiently harvest wideband wireless energy from 1.7 to 2.7 GHz under dual-polarization modes. The detailed experimental results will be presented at the EuCAP conference in March 2020.

IV. Conclusion

A compact (55 × 55 ×1.0 mm^3) dual-polarized rectangular slot rectenna is proposed for ambient RF energy harvesting. A wideband operational bandwidth has been achieved (1.7-2.7 GHz) using perpendicular CPW and microstrip line, respectively. A novel rectifier topology has been introduced using two shunt diodes. The simulation results have been presented and showed that RF-DC conversion efficiency is greater 40% within the frequency band of interested at -3.0 dBm received power. Finally, the detailed experimental results will be presented at the EuCAP conference in March 2020.

References

[1] M. Zorzi, A. Gluhak, S. Lange, and A. Bassi, “From today’s INTRAnet of things to a future INTERnet of things: A wireless- and mobility related view,” *IEEE Wireless Commun.*, vol. 17, no. 6, pp. 44–51, Dec. 2010.

[2] K. Shafique, B. A. Khawja, M. D. Khurram, *et al*, “Energy harvesting using a low-cost rectenna for internet of things (IoT) applications,” *IEEE Access.*, vol. 6, pp. 30932–30940, June. 2018.

[3] A. Georgiou, G. V. Andia and A. Collado, “Rectenna design and optimization using reciprocity theory and harmonic balance anlalysis for electromagnetic (EM) energy harvesting,” *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 444–446, May. 2010.

[4] C. Song, Y. Huang, P. Carter, J. Zhou. S. Yuan. Q. Xu and M. Kod, “A novel six-band dual CP rectenna using improved impedance matching technique for ambient RF energy harvesting,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 3160–3171, Jul. 2016.

[5] S. Shen, Y. Zhang, C. Chiu and R. Murch, "An ambient RF Energy harvesting system where the number of antenna ports is dependent on frequency, ” *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no. 9, pp. 3821-3832, Sept. 2019.

[6] S. Shen, C.-Y. Chiu and R. Murch, "A dual-port triple-band L-Probe Microstrip patch rectenna for ambient RF energy harvesting, ” in *IEEE Antennas and Wireless Prop. Letters*, vol. 16, pp. 3071-3074, 2017.

[7] C. Song, Y. Huang, J. Zhou, J. Zhang, S. Yuan and P. Carter., “A high-efficiency broadband rectenna for ambient wireless energy harvesting,” *IEEE Trans. Antennas Propag.,* vol. 63, no. 8, pp. 3486–3495, May 2015.

[8] X. Yang, C. Jiang *et al*, “A novel compact printed rectenna for data communications systems, ” *IEEE Trans. Antennas Propag.,* vol. 61, no. 5, pp. 2532–2539, May 2013.

[9] H. Sun and W. Geyi, “A new rectenna with all-polarization-receivign capability for wireless power transmission, ” *IEEE Antennas and Wireless Prop. Letters*, vol. 15, pp. 814-817, 2016.

[10] Guang-Hua Sun, Sai-Wai Wong, Hang Wong, “A Broadband Antenna Array Using Full-Wave Dipole, ” *IEEE Access*, vol. 5, pp. 13054-13061, 2017.

[11] N. P. Basta, E. A. Falkenstein *et al*, “Bow-tie rectenna arrays, ”*In Proceeding of IEEE Wireless Power Transfer Conference (WPTC)*, Boulder, CO, USA, 2015

[12] www.cst.com.

[13] C. Song et al., “Matching network elimination in broadband rectennas for high-efficiency wireless power transfer and energy harvesting,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 5, pp. 3950–3961, May 2017.

[14] V. Marian, C. Vollaire, J. Verdier, and B. Allard, “Potentials of an adaptive rectenna circuit,” *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 1393–1396, Dec. 2011.